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MECHANICAL PROPERTIES, MACHINABILITY AND CORROSION RESISTANCE OF ZAMAK5 ALLOYED BY COPPER

Due the importance of using commercially Zamak5 in a wide range in industrial applications, however, this study was focused on the enhancing its machining issues by adding pure copper, so the effect of the addition of (1 to 3)% Cu to commercially Zamak5 on its mechanical properties, microhardness, surface texture and corrosion resistance was investigated. A CNC machining tests, microhardness tests, corrosion test, compression test, and microhardness test were performed. It was found that there is an enhancement on the flow stress at 0.2 strain of about 19% for 3% Cu addition followed by 17% and 15% in the case of 2% Cu and 1% Cu respectively. There was an enhancement in microhardness of about 11.6% in the case of 3% Cu addition. The surface finish was improved by increasing the number of copper contents (1 to 3)% to the base material Za5. Polarization measurements revealed that 3% alloy specimen inhibit the corrosion by more than 70% compared with the blank sample.

Keywords: Zamak5; Machinability; Mechanical Behavior; Copper; Corrosion Resistance

1. Introduction

Zinc-aluminum alloys form the basis of several commercial alloys including ZA-8, ZA-12, ZA-27, and ILZRO-12 [1-8]. Zn-Al alloys have emerged as a potential cost, effective energy, and environmentally-friendly system for substituting several ferrous and non-ferrous alloys in various applications [9-11], Zinc, which is the main element in the ZA-12 alloy, has an HCP lattice structure. Due to the restricted number of slip systems in the HCP lattice, the ductility is limited [9,12]. On the other hand, heat treatment applied to Zn-Al alloys to increase their strength and hardness is usually accompanied by a loss of ductility [9,10,13]. Zinc alloys have several advantages over other nonferrous alloys. They can be cast in much thinner walls, and to tighter dimensional tolerances. Zinc alloys allow the use of very low draft angles in some cases, zero angles are possible. On the other hand, all zinc casting alloys have excellent machining properties with long tool life, low cutting forces, good surface finish, low tool wear, and small chip formation. Common machining performed on these alloys includes drilling, tapping, reaming, broaching, turning, and milling [14]. The metallurgical and micromechanical aspects of the factors controlling microstructure, unsoundness, strength, and ductility of as-cast alloys are complex. It is well known that solidification processing variables are of a high order of importance. In the as-cast state, an alloy may possess within individual grains, a dendritic network where solute concentration varies continuously, a complex dispersion of second phases, and possibly porosity and inclusions [15]. The research works [11,16-18] showed that the addition of alloying elements including copper, silicon, magnesium, and nickel can improve the mechanical and tribological properties of zinc-aluminum alloys. The use of steel slag in concrete production can be promising in the construction industry [19]. The role of Cu was systematically investigated for Zn-27%Al and Zn-40%Al alloys in [20,21]. It is reported that Cu is beneficial for wear resistance up to 2 wt.%, while for higher content no significant improvement in material performance can be appreciated. The microstructure of cast Al-Cu alloys is composed of dendrites of solid Al solution and creates a brittle and roughly continuous multi-phase network of eutectics at the grain boundaries [22]. Crystallography, grain size, and form, grain heterogeneity, impurity inclusions, and residual stress owing to cold work are all key metallurgical elements in corrosion. The results revealed significant growth of dendritic arms during the solidification process, which is accompanied by disintegration and fragment production [23].

According to the literature regarding this work, no or little work performed, however In the present work, enhancing the quality of surface together with microhardness and mechanical

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characteristics is very important in industry as well as the corrosion resistance of Zamak5 alloyed after adding different percentages of pure copper, so this form the main objective of the study.

2. Materials and methods

2.1. Materials

Commercially zinc-aluminum casting alloy (Zamak5) having a chemical composition of 4 wt.% Al-1wt% Cu-0.06wt.% Mg-0.1wt.% Fe-0.005wt.% Pb-0.004wt.%. Cd-0.003wt.%Sn and balance Zn were used throughout this study and it will be reviewed as Za5. The base material used throughout this work is available in the form of blocks. Where the density for Zamac5 is 6.6 gcm^{-3} and the melting point range is 380-386°C.

2.1.1. Copper

Copper powder of 99.8% purity was used as an alloying element to be added to Za5. Its melting point is 1083°C, and its density is 8.2 gcm^{-3} at 20°C, where the shape of copper particles is a sphere shape with size less than 225 µm, also nitric acid, aluminum oxides, finer abrasive paper, optical microscope were used in the microstructure test.

2.1.2. Preparation of Zamak5-Copper Alloys

Three alloys in addition to commercially Za5 were prepared by addition of 1, 2, and 3% of Cu to the parent alloy, where the main binary Zn-Al phase diagram is shown in Fig. 1. The maximum addition of Cu is 3%, this due to maximum solubility of copper in aluminum is about 3% at the melting point of zinc 419°C.

2.2. Equipment

A set of machines and equipment were used throughout the experimental work namely; an electric resistance furnace (Type Carbolite) with 0-1750°C, digital microhardness tester (Model HWDM-3), Universal Testing Machine (MTS) with 250 KN capacity, CNC milling machine (KM 3000), surface tester (Pocket Surf-III), H.S.S. face milling cutter (Q30, 6), microscope type NIKON 108, CNC lathe machine (Type Boxford 160), casting mold (Brass), SEM type FEI Quanta FEG 450.

2.3. Experimental procedures

2.3.1 Preparation of test specimens

The binary Za5-Cu alloys were prepared by adding the predetermined amount of copper powder into molten Za5 at 650°C under cryolite flux. The temperature was kept constant for five minutes and the alloy was stirred for two minutes before pouring it into the casting mold. Besides, 12 specimens of 10 mm diameter and 10 mm height ($D/h = 1$) were prepared for investigating the mechanical behavior of each type from the prepared alloys depending on the compression test. The casting process is shown in Fig. 2.

2.3.2. Compression test

The prepared cylindrical specimens were subjected to the compression test using the previously mentioned Universal Testing Machine with 250 KN at a crosshead speed of 10 mm/min. The load-deflection curve was obtained for each type of the prepared alloy from which the true stress-true strain was determined. Three tests were carried out on each Za5-Cu alloy and the mean value was calculated and presented.

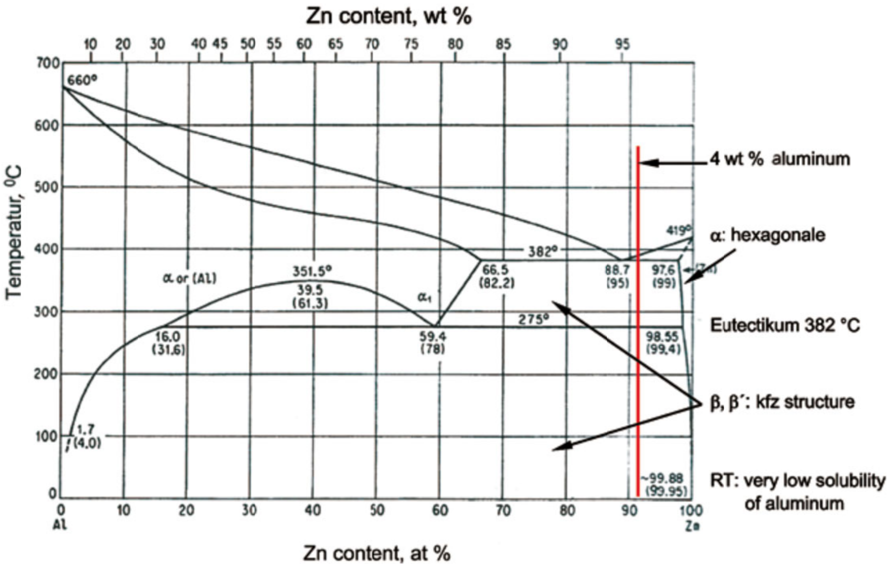

Fig. 1. The binary Al-Zn phase diagram [13]

Fig. 2. Casting of Al-Cu alloys process

2.3.3. Machinability test and surface roughness test

The machining test was carried out on the CNC milling machine (KM3000) and a surface tester (pocket Surf III) also used to determine the roughness values (*Ra*). The process of machining was carried out under conditions presented in TABLE 1.

TABLE 1

Cutting parameters of Za5-Cu alloys

Depth of cut (*d*) (mm)	**Cutting speed (*v*) (mm/sec)**	**Feed rate (f_r) (mm/min)**
0.10	576	50
0.15	864	100
0.20	1151	150
0.25	1439	200
—	1727	250

The path of CNC end mill tool (*D* = 12 mm) is shown in Fig. 3, and fixed for all experimental work.

A brass mold is designed and manufacture in order to be used in casting of different work pieces as shown in Fig. 4a, so two specimens of (50*25*25) mm from each Za5-Cu alloy and pure Za5 were prepared for the machining process as shown in Fig. 4b.

Fig. 3. Path of the cutting tool from A to B

2.3.4. Microhardness test

Microhardness test was carried out using HWDM-3 microhardness tester at 500 gm force on each Za5-Cu alloy, five microhardness values were taken, from which the mean value was calculated as shown in Fig. 5.

2.3.5. Microstructure test

In this test, the general microstructures of pure Za5 and Za5-Cu in the as cast condition were determined after grinding, polishing and etching in order to get clear microstructures.

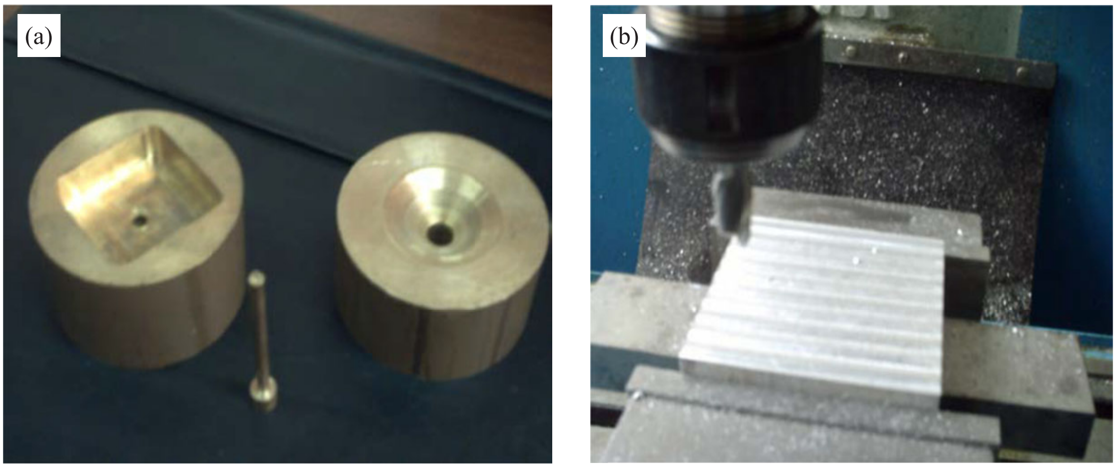

Fig. 4. a) Brass mold used to produce the casted work piece b) Machining process

Fig. 5. Microhardeness tester

Zamak5 and microalloys were chemically etched using a solution of 5 ml HCl and 100 ml distilled water for 90 seconds. Photomicrographs were obtained using the NIKON 108 type microscope at magnification of 250×.

2.3.6. Potentiodynamic Polarization Test

Two different Zamak5 alloyed by copper (1% and 3%) and pure Za5 work pieces were tested for corrosion inhibition in 3% wt. NaCl solution. For potentiodynamic polarization tests, the exposed area of the specimens' surfaces was adjusted to be 1 cm^2. Electrodes were polished with emery papers of fine grade and degreased with acetone and rinsed with distilled water. Electrochemical experiments were carried out with a VoltaLab (PGZ 100, U.S.) potentiostat in a double-wall three-electrode glass cell. All reported potential values are versus the saturated calomel electrode (SCE) as a reference electrode and all measurements were carried out at room temperature. A graphite electrode was used as the auxiliary electrode. All glassware for electrochemical experiments were carefully cleaned and rinsed with distilled water. The polarization curves were measured from a cathodic potential of –1200 mV to an anodic potential of –1000 mV with respect to the open circuit potential (OCP) at a scan rate of 10 mV/s.

3. Results and discussions

In this section, the effect of Cu addition on the microstructure, microhardness, mechanical behavior, machinability, and corrosion resistance of Za5 will be presented and discussed.

3.1. Effect of Cu addition on the microstructure of Za5

It can be seen from Figure 6-a structure of pure Za5 consists of aluminum-rich $\alpha\beta$ dendrites and zinc-rich interdendritic β phases which have poor mechanical properties and this is consistent with [20]. The addition of copper produced some copper-rich particles in the interdendritic regions of these alloys which decrease the secondary dendritic arm as shown in Figs. 6b, 6c, and 6d, this resulted in the enhancement of the mechanical properties, and this consistent with [24] that reported in case of alloy containing Cu in percentage higher than 2%, like for instance in Zamak2, also Cu-rich phase (CuZn4) can be easily found, also is consistent with [25] that revealed in case of the Zn$_3$Al alloy the typical solidification microstructure was composed of primary η – Zn rich dendrites surrounded by eutectic areas.

It is clear from Fig. 7, Fig. 8, Fig. 9, and Fig. 10 the SEM images after copper additions up to 2% that there is an inter-

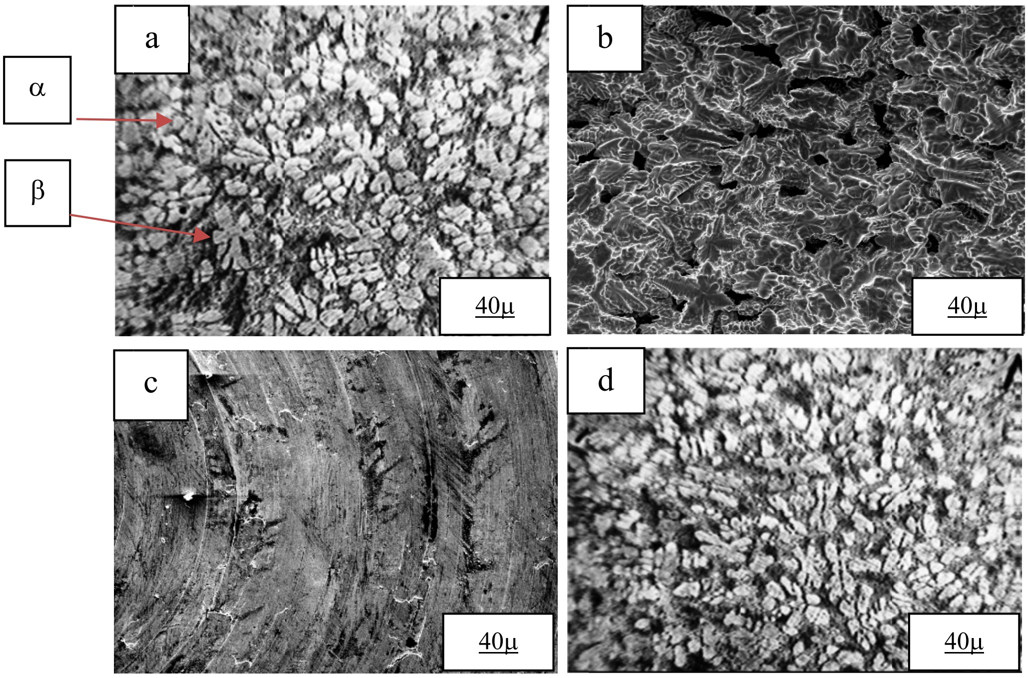

Fig. 6. Photomicrographs showing the general microstructure of Za5 and Za5-Cu Alloys, a) Za5, b) Za5-1% Cu, c) Za5-2% Cu and d) Za5-3% Cu

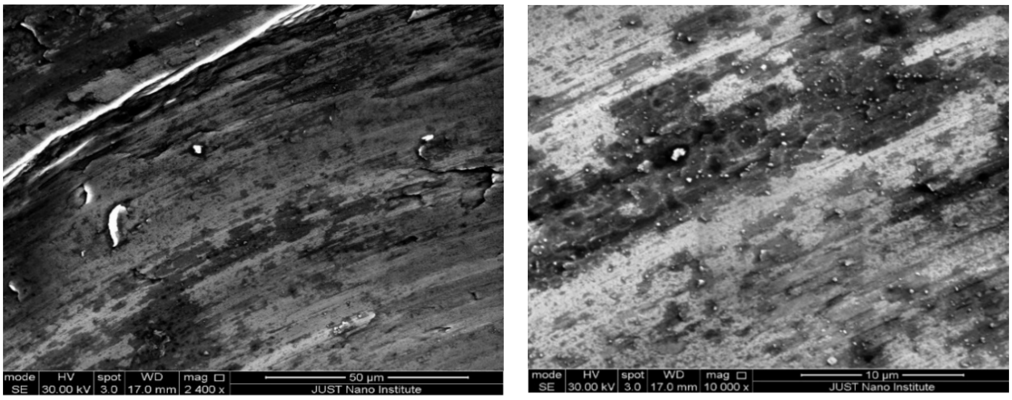

Fig. 7. SEM images for pure zamak5 at 2400× and 10000×

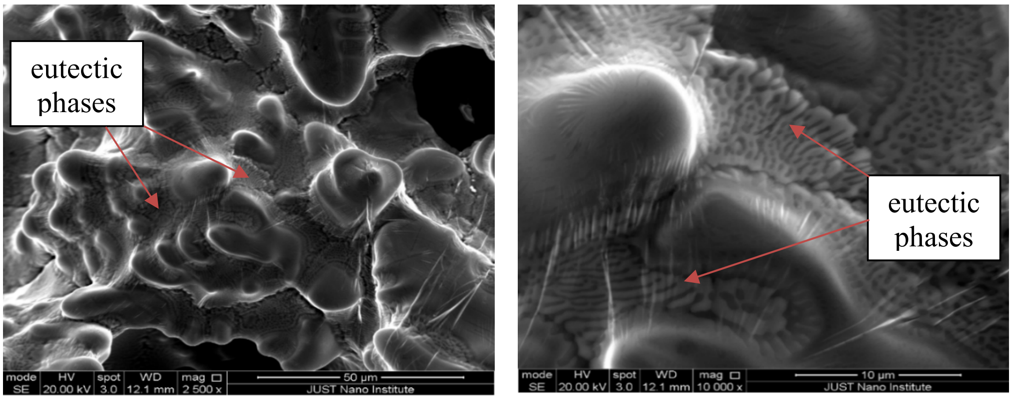

Fig. 8. SEM images for ZA5-1% Cu at 2500× and 10000×

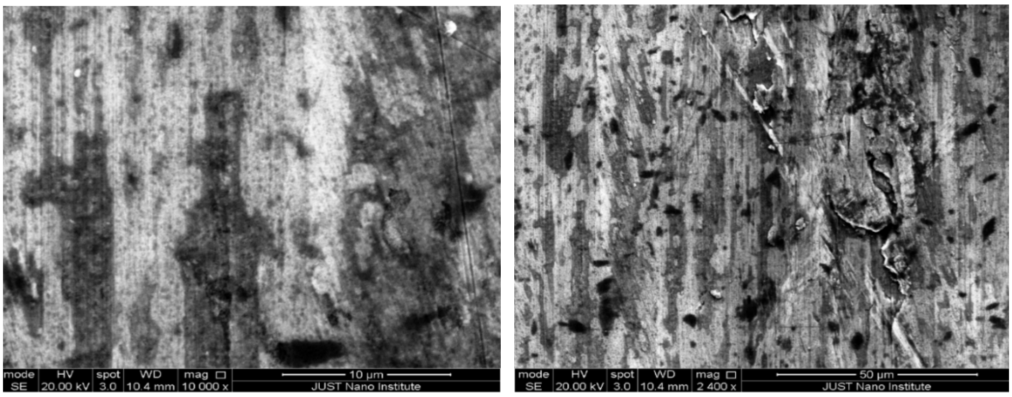

Fig. 9. SEM images for ZA5-2% Cu at 10000× and 2400×

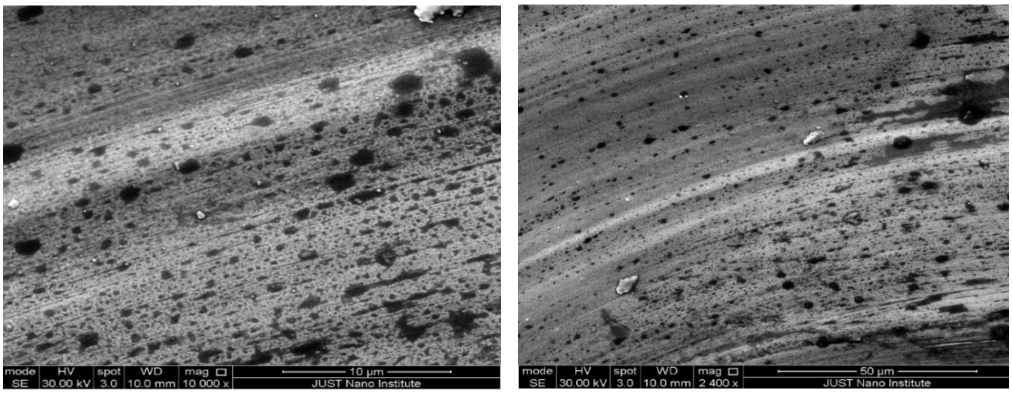

Fig. 10. SEM images for ZA5-3% Cu at 2400× and 10000×

metallic compounds formed in the structure, However, most of mechanical properties were enhanced, and this can be related to the stress-strain curve for all Za5 and Zam5-Cu alloys in Fig. 11. Other studies [26] revealed that the addition of Mg to the hypoeutectic alloy Zn-Al causes changes of the alloy structure and morphology of the eutectics and the obtained Zn phase.

3.2. Effect of Cu addition on the mechanical characteristics of Za5

It was obvious from Fig. 11 that the addition of copper to Za5 resulted in enhancement of mechanical characteristics for all copper additions, so the maximum improvement in flow stress (at 0.2 strain) was attained at 3% Cu addition by 19% followed by 17% and 16% for 2% Cu and 1% Cu respectively. The mechanical properties mainly depend in two factors, the first one is the chemical composition and the second is the casting conditions. Most researchers reported that it must be emphasized that many of the cited papers report different values of mechanical properties for the same alloys. This can be easily explained considering the deferent samples sizes and casting parameters (mold temperature, runner and gating system, etc.), i.e., deferent solidification and cooling rates, which result in dissimilar microstructure and casting defects distribution [27].

3.3. Effect of Cu addition on the hardness of Za5

The addition of Copper increased hardness by about 11.6%, followed by 10.7%, 1.8% for 3% Cu, 2% Cu, and 1% Cu respectively, as shown in Fig. 12. This enhancement due to the formulation of intermetallic compound Al_2 Cu. The improved microhardness in number can be attributed to the large grain boundary area associated with the fine structure of the microalloy. The hardening effect stems from the ability of the fine grained structure to resist atomic sliding upon loading, since the grain boundaries act as pinning points that block the dislocation motion. Because the lattice structure of adjacent grains differs in orientation, the dislocations require more energy to move from one direction to another. Hence, the yield strength and microhardness characteristics improve [28].

3.4. Effect of Cu addition on the machinability aspects

3.4.1. Effect of depth of cut on the surface quality of Za5 alloyed by copper

It is well known that the depth of cut slightly affects the machined surface quality when compared to the cutting speed and feed rate. The experimental analysis of this factor was achieved

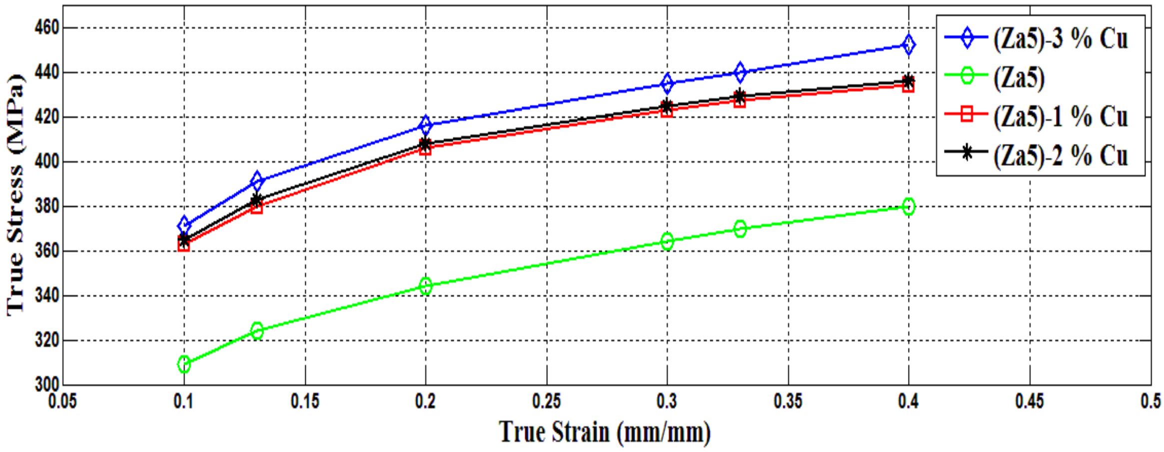

Fig. 11. True stress – True strain of Za5-Cu Alloys

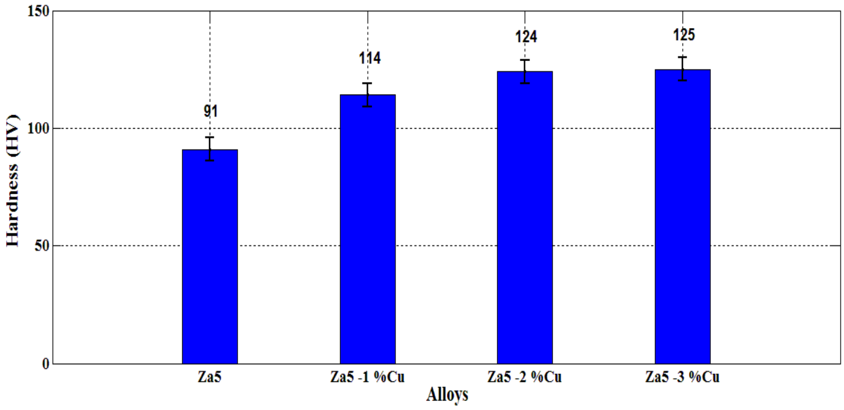

Fig. 12. Effect of Cu addition on the hardness of Za5

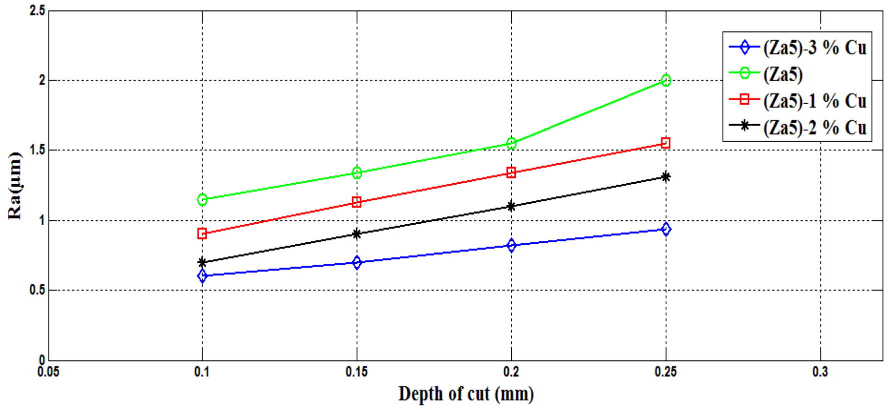

Fig. 13. Depth of cut versus average surface roughness *Ra* at v = 864 mm/sec and f_r = 100 mm/min

during the milling of several specimens at different depths and constant speeds and feed rates as shown in Fig. 13. The surface finish is improved by increasing the number of copper contents (1-3)% to the base material Za5. This clear because harder material gives a better surface finish.

3.4.2. Effect of cutting speed on the surface quality of Za5 alloyed by copper

It can be seen from Fig. 14 that the surface roughness of the original Za5 alloy is increased as the cutting speed increases from 576 mm/sec to 864 mm/sec. the subsequent increase from 864 mm/sec to 1727 mm/sec in the speed resulted in enhancement of the surface finish. This can be explained by the formulation of the built-up edge at low speeds which reach its maximum volume after which it breaks by the generated high pressure and elevated temperature, so the cutting edge returns to its initial geometry by which the surface finish improved. It was observed that the built-up edge varied according to the copper content percentages. At the upper value of copper addition, the built-up phenomena weren't observed due to the enhancement in the hardness. The result in [29] shows that the cutting speed is the most significant factor influencing aluminum epoxy surface roughness.

3.4.3. Effect of feed rate on the surface quality of Za5 alloyed by copper

It can be seen from Fig. 15 that as the feed rates increases from 50 mm/min to 250 mm/min the machined surface deteriorates irrespective of the copper addition. This is obvious because at high values of feed rate the successive traces of cutting edges increase and larger projections remain onto the machine surfaces, other studies [30] revealed that addition of 4% Cu to ZA21 alloy resulted in better surface quality at all cutting speeds, depth of cut and feed rates, which may be attributed to the grain refining caused by the copper addition which also resulted in improvement of its hardness, both of which reduces surface roughness i.e. improves surface quality.

3.4.4. Effect of copper addition on the characteristics of chip

It can be seen from Figs. 16(a) and (b) that the formed chip in the ZA5 alloy before and after addition of all Cu percentages is of the discontinuous type. This is expected, because the type of chip in the milling process is function of the process and not affected by process parameters. Furthermore, the discontinuous chip formed in case of AZ5-Cu is finer than that of the alloy

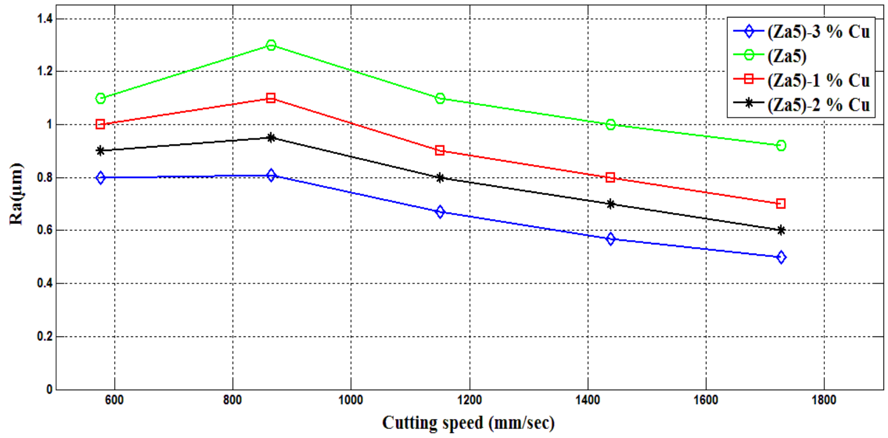

Fig. 14. Cutting velocity versus average surface roughness *Ra* at d = 0.15 mm and f_r = 100 mm/min

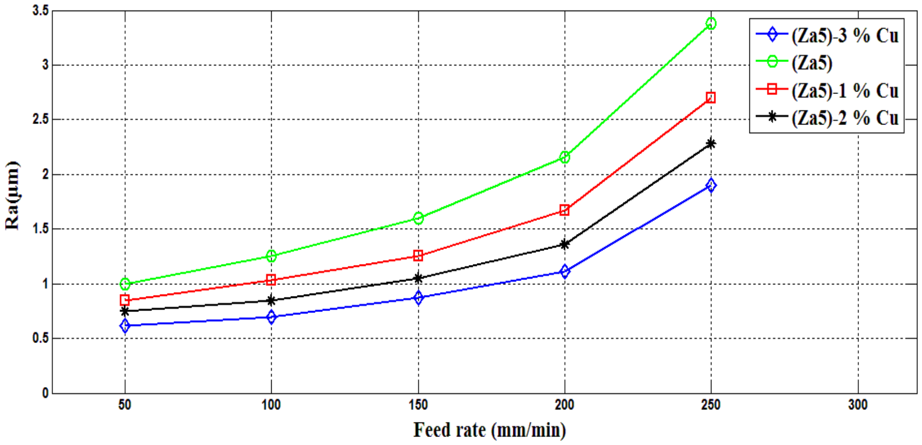

Fig. 15. Feed rate versus the average surface roughness (*Ra*) at $d = 0.15$ mm and $v = 864$ mm/sec

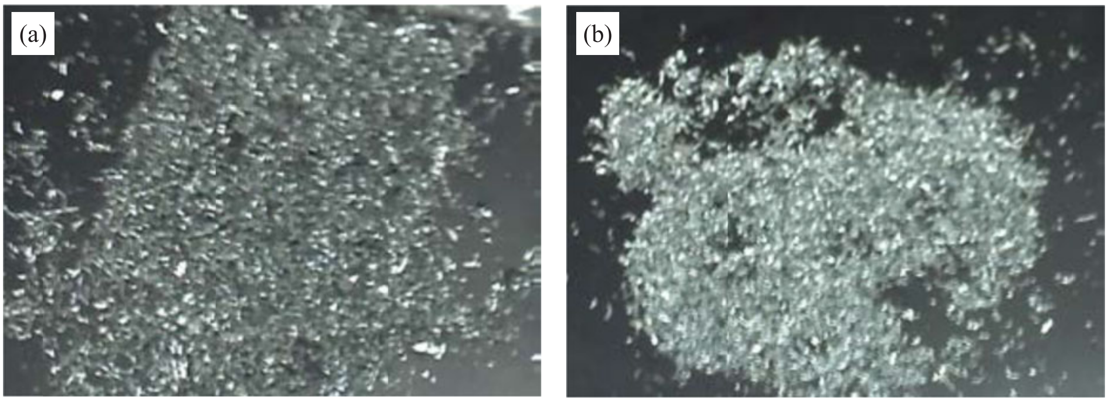

Fig. 16. Type of chips, (a) ZA5, (b) ZA5-Cu

before the addition. This can be attributed to the increase in the hardness of the alloy after copper addition.

3.5. Effect of copper addition on the corrosion resistance of Zamak5 alloy

In Fig. 17 the addition of Cu showed reasonable corrosion inhibiting behavior for steel alloy in 3% NaCl. Polarization measurements suggest that 3% alloy specimen inhibit the corrosion by more than 70% compared with the blank sample. However, the inhibition efficiency was around 50% for 1% alloy sample.

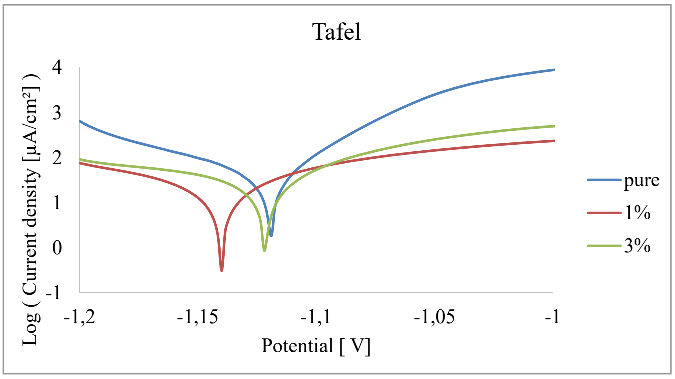

Fig. 17. Tafel Plot of the reference and copper-alloyed Zamak5

This study demonstrated the same trend in corrosion inhibition with differences in inhibition efficiency absolute values due to the individual technique parameters and sensitivity.

The generated Tafel plots were analyzed by extrapolation to evaluate the corrosion potential (E_{corr}) and the corrosion current densities (I_{corr}). Tafel parameters are represented in TABLE 2 [22].

Concerning the main alloying elements, Cu has been found to have a beneficial effect on the atmospheric corrosion resistance. Also Al improves the corrosion resistance. In fact, the corrosion rate of the ZA alloys in water was demonstrated to increase below pH 6.0 and above pH 11.5, meanwhile for ZA27 it resulted one-third that of other Zn-Al alloys [31,32].

TABLE 2

Tafel parameters results of the tested specimens

Parameter	% Cu		
	Pure (Ref.)	1%	3%
$E_{corrosion}$ (mV)	–1124.7	–1144.8	–1126.5
$i_{corrosion}$ (µA/cm²)	35.3085	15.7285	9.4670
R_p (ohm.cm²)	245.31	744.68	526.38
Beta a (mV)	34.0	67.6	26.7
Beta c (mV)	–66.1	–80.5	–35.9
Corrosion Rate (µm/Y)	268.1	119.4	71.9
Inhibition Efficiency %	—	55	73

5. Conclusions

The following conclusions may be drawn from this work:

1. There is a direct relationship between copper addition and the enhancement in mechanical behavior.
2. The optimum copper addition from the microhardness point view was 3% Cu which improves the microhardness by 11.6%.
3. The surface finish was improved by increasing the number of copper contents (1-3)% to the base material Za5. This clear because harder material gives a better surface finish.
4. The addition of copper produced some copper-rich particles in the interdendritic regions of these alloys which decrease the secondary dendritic arm and therefore the mechanical properties were enhanced.
5. Further increasing in Cu addition to Za5 didn't affect the mechanical properties because of the maximum solubility of Cu in Za5 about 3%, so the maximum addition of Cu is 3%, this due to maximum solubility of copper in aluminum is about 3% at the melting point of zinc 419°C.
6. The addition of Cu showed reasonable corrosion inhibiting behavior for steel alloy in 3% NaCl.

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